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THERMAL CONDUCTANCE OF PRESSED BIMETALLIC CONTACTS AT LIQUID NITROGEN TEMPERATURES

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The thermal conductance of one aluminum and one stainless steel pressed metal contacts has been measured near 77 K, with applied forces from 8.9 N to 267 N. Both 5052 or 5083 aluminum were used as the upper contact. The lower contact was 304L stainless steel. The thermal conductance is linear in temperature over the range of measurement and ranged from roughly 9 to 21 mW/K. There is no difference in conductance between the two aluminum alloys. Extrapolating the data to zero applied force does not result in zero thermal conductance. A possible cause of this anomalous effect is discussed.

INTRODUCTION

Large Dewars often use aluminum radiation shields and stainless steel vent lines. A simple, low cost method of making thermal contact between the shield and the line is to deform the shield around the line.[1] The resulting bimetallic joints involve light contact forces. A knowledge of the thermal conductance of such a joint is needed to thermally analyze the system. A series of thermal conductivity measurements were made at liquid nitrogen temperatures (77 K) over a range of applied contact forces from 8.9 N to 267 N. One surface was 304L stainless steel. Two different alloys of aluminum (5052 and 5083) were used for the other surface. These materials were chosen because they are commonly used in Dewar construction.

METHOD & RESULTS

The configuration and details of the apparatus have been described previously [2] and are summarized here. The measurements were made with the lower sample connected to a liquid nitrogen bath at 77 K. A range of forces from 8.9 N to 267 N was applied to the upper sample by a rocker arm and insulation assembly. The contact force is applied by a wire that runs to an external room temperature load cell and gear motor. Heat is applied to the upper sample and the temperature drop across the contact is measured by Platinum Resistance Thermometers (PRT) mounted in each sample.

Overall dimensions of the sample pairs were 12.7 mm diameter and 8.89 mm height for the upper sample and 10.2 mm diameter and 15.2 mm height for the lower sample. The larger diameter of the upper sample assured that contact was made despite slight misalignments of the samples. Sample pair #1 had a 5052 aluminum upper sample, while for sample pair #2, the upper sample was 5083 aluminum. The lower sample for both pairs was 304L stainless steel. Contact surface finish was 0.8 μm for the aluminum and 1.6 μm for the stainless steel.

The samples were cleaned in methanol before installation in the apparatus, to avoid the possibility of grease or other substance being present on the contact surfaces. Once the samples were installed, a nominal force (roughly 9 N) was applied, the cryostat was evacuated to a pressure of $<10^{-5}$ torr, and then cooled to liquid nitrogen temperature. Data were taken at 7 forces (8.9, 18, 36, 53, 89, 178, and 276 N), a range of heater powers from 0 to 10.0 mW, and a bath temperature of 77 K. The thermal contact conductance, k, was found for each force by fitting the upper (T_h) and lower (T_c) sample temperatures, and heater powers (Q) data to the function:

$$k = Q\,(T_h - T_c)^{-1} \qquad (1)$$

Prior to fitting the data, the T_h values were corrected for the bulk conductance of the samples. The thermometers measure the temperature a short distance from the contact. Part of the measured temperature difference is due to the bulk conductivity of the samples. Correcting for this effect results in a contact conductance of

$k = Q\,[T_h - T_c - Q(1/k_a + 1/k_s)]^{-1}$ (2)

where k_a and k_s are $□_{bulk}$ (A/ L) for the aluminum and stainless steel respectively and $□_{bulk}$, A, and L are the respective bulk conductivity, cross-sectional area and thermometer to contact distance. The bulk conductivity at 77 K of stainless steel is 8 W/m-K and that of aluminum is 56 W/m-K. [3] The aluminum correction was insignificant and could be ignored. The stainless steel correction resulted in a 5-10 % change in the fitted contact conductance.

DISCUSSION & CONCLUSIONS

The plots of Q vs. (T_h - T_c) for the corrected data for each force as well as a best fit of Equation 2 are shown in Figures 1 and 2 for sample pairs #1 and #2, respectively. Table 1 presents the calculated thermal conductance as a function of applied force and the estimated error for a few representative points. The error principally stems from the error in the measurement of the sample temperatures T_h and T_c. These results are also shown in Figure 3.

Table 1. Thermal Contact Conductance of Aluminum/Stainless Steel at Liquid Nitrogen Temperatures.

Sample Pair #1 Al 5083 / SS 304 L		Sample Pair # 2 Al 5052 / SS 304 L	
Force (N)	k (mW/K)	Force (N)	k (mW/K)
9	8.9463 ± 0.264	9	9.3548 ± 0.321
18	10.244	18	9.9144
36	9.5229	36	10.413
54	10.840	54	11.678
90	12.810	90	15.665 ± 0.870
180	16.758	180	18.488
270	22.864 ± 0.750	270	21.891 ± 1.67

In examining Table 1 and Figure 3, it can be seen that the thermal conductance does not approach zero as the force approaches zero. Rather, the thermal conductance appears to be approximately 9 mW/K at 0 N. This anomaly was repeatable; it was the same for both samples. It does not appear to be due to binding or to an offset in the force mechanism. The load cell calibration was within 0.001%. No hysteresis was observed, nor could a parallel heat path account for the effect, since the residual gas pressure and thermal radiation are too small.

An attempt was made to measure the parallel heat path through the lever arm by calibrating the conductance of the lower sample to liquid nitrogen bath thermal path. This calibration was done with the rocker arm removed and the upper sample just resting on the lower sample. Unfortunately, uncertainties in measuring the bath temperature (±~170 mK by measuring the bath pressure) limited the usefulness of this method. Within the limitation of the method, no significant parallel path could be found.

Finally an attempt was made to measure the conductance at very small forces. For this measurement, the apparatus was modified. The rocker arm was reinstalled with a return spring. The spring allowed the force to be completely removed from the sample. Friction in the system made it difficult to accurately control and measure forces less than 9 N, therefore only qualitative results could be obtained. The apparent offset for forces greater than 9 N was reproduced. At lower forces the conductivity appears to decrease rapidly toward zero.

One possible explanation for this behavior lies in the microscopic nature of the contact. For very small forces (« 9 N) the contact is restricted to few points (~3). Each of these points is lightly loaded at less than the yield stress. As the stress is increased, the actual contact area increases rapidly as does the number of contacts, resulting in a rapid increase in conductance. Eventually there is local yielding at the contact points. Once the yield stress has been reached, the total contact area, A_t, is

$A_t \approx (F-F_o)/□_y + A_o$, for $F > F_o$ (3)

where A_o and F_o are, respectively, the contact area and the force when the yield stress is reached, F is the applied force, and $□_y$ is the yield stress. In this region A_t is a linear function of the applied force. But,

$k \quad (nA_t)^{1/2}$ (4)

where n is the number of contacts. [4,5] Combining Eqs. (3) and (4) yields:

$k \quad n^{1/2}\,(F/□_y - F_o/□_y + A_o)^{1/2}$, for $F > F_o$ (5)

For forces > 9 N, the conductance is approximately a linear function of the applied force (Fig.□3). The number of contact points must be increasing with increasing force. Writing n F^r in Eq. (5) and assuming ($F \gg F_o$) yields

$$k\square\ F^{(r+1)/2} \tag{6}$$

This is consistent with the data if $r \approx 1$. (For larger forces than reported here, a value of $r \approx 0.76$ has been reported for aluminum at room temperature. [4]) Note that the conductivity is not very sensitive to the value of r within the range of the data reported here. In either case, in the high force regime, the increasing conductance comes roughly equally from increasing the number of contacts and increasing the contact area of already existing contacts.

In conclusion, within the range of error, the data from sets #1 and #2 is indistinguishable, suggesting that identical thermal conductance can be realized with either the use of 5052 or 5083 aluminum. There are two conductance regimes. At very low forces (« 9 N) the conductance increase rapidly until a critical force is reached. At higher forces, the contact conductance is less sensitive to changing the force. In this regime both the number of contacts and their individual areas increase in direct proportion to the force.

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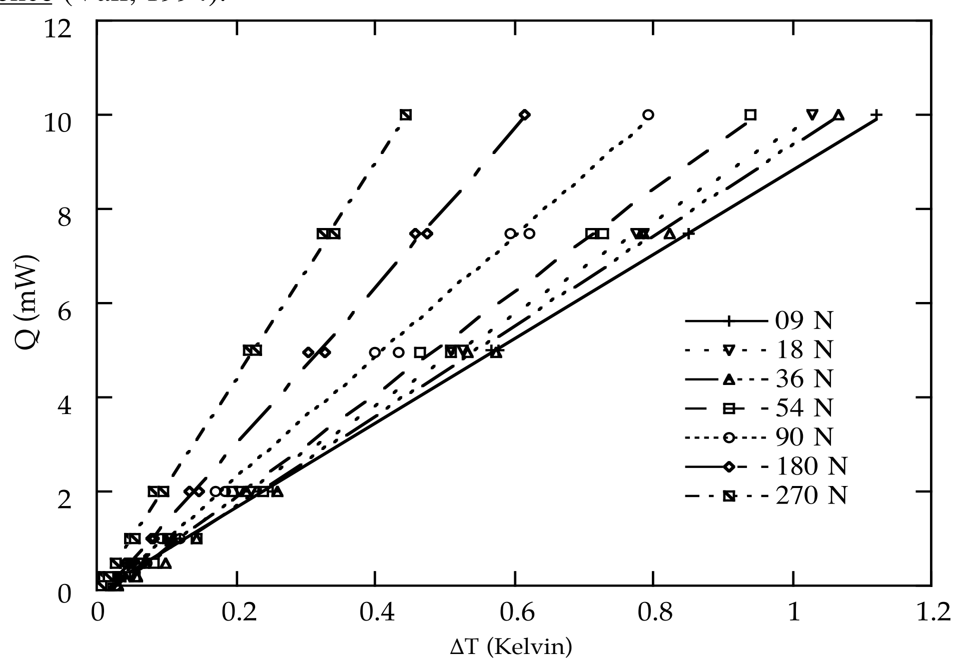

Figure 1. AL 5083/ SS 304 L Sample Pair #1

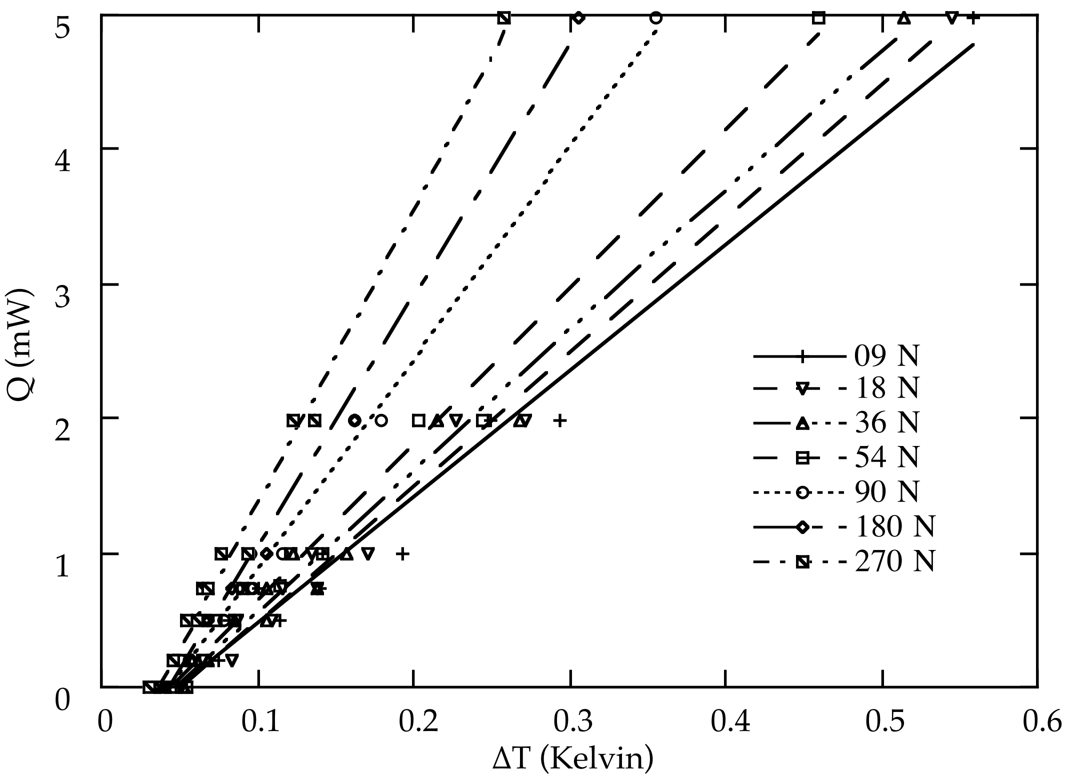

Figure 2. AL 5052/SS 304 L Sample Pair #2

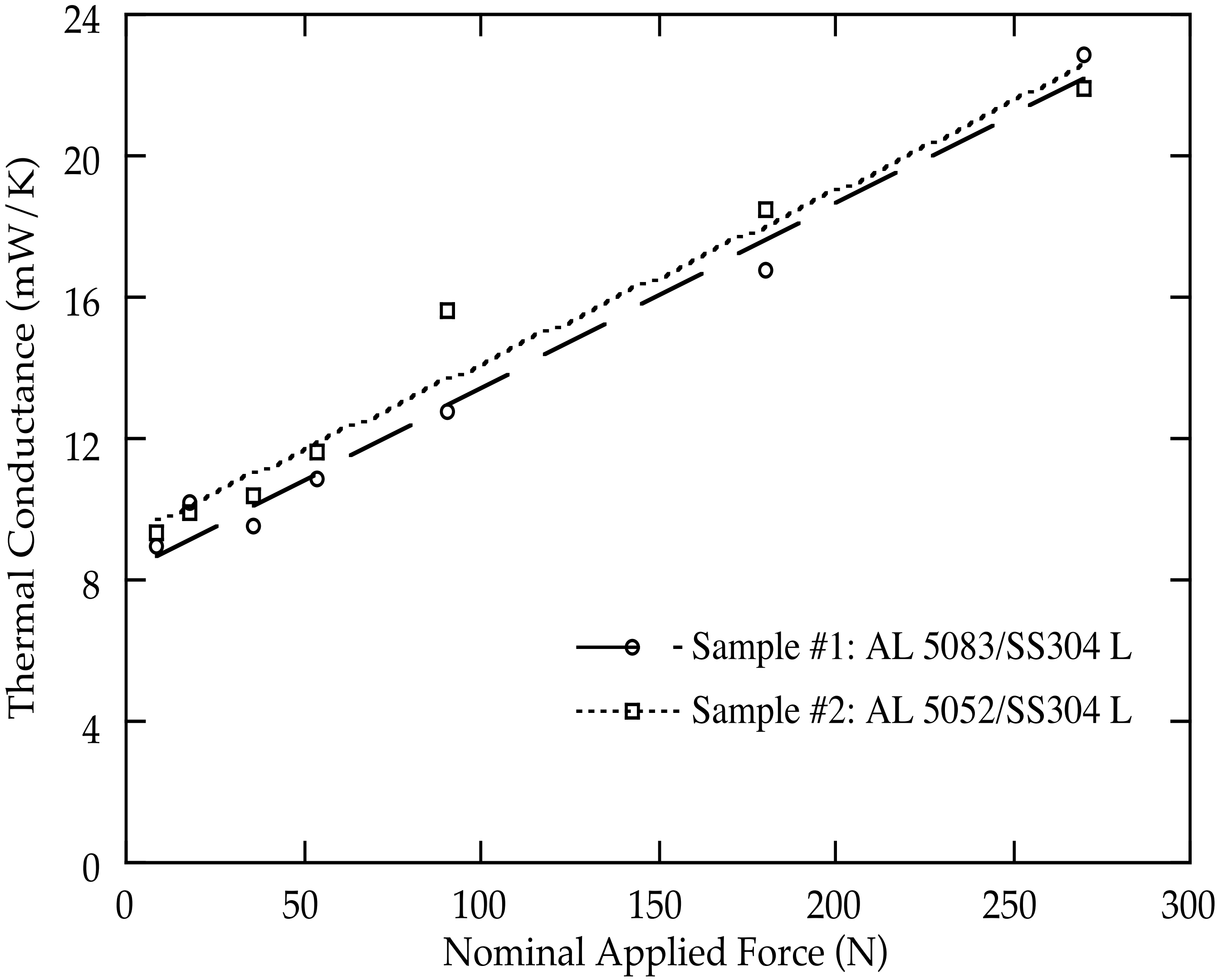

Figure 3. Thermal conductance vs. applied force